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This report describes the multi-user radiofrequency radiation exposure facilities for bio-effects research in use at the Health Effects Research Laboratory, Research Triangle Park, NC. Four facilities are described: (1) a 100 MHz CW exposure system, (2) a 2450 MHz CW exposure system, (3) a 2450 MHz AM exposure system, and (4) an X-band pulsed RF exposure system. The individual facility descriptions include construction details, specifications, photographs, circuit drawings and block diagrams. All of the facilities incorporate environmental control systems and three have RF power-level regulation.

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RADIOFREQUENCY RADIATION EXPOSURE FACILITIES FOR BIO-EFFECTS RESEARCH AT THE HEALTH EFFECTS RESEARCH LABORATORY RESEARCH TRIANGLE PARK, NORTH CAROLINA

by

Joseph S. Ali and Claude Weil

Biological Engineering Branch
Health Effects Research Laboratory
Research Triangle Park, NC 27711

HEALTH EFFECTS RESEARCH LABORATORY
OFFICE OF RESEARCH AND DEVELOPMENT
U.S. ENVIRONMENTAL PROTECTION AGENCY
RESEARCH TRIANGLE PARK, NORTH CAROLINA 27711

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FOREWORD

The many benefits of our modern, developing, industrial society are accompanied by certain hazards. Careful assessment of the relative risk of existing and new man-made environmental hazards is necessary for the establishment of sound regulatory policy. These regulations serve to enhance the quality of our environment in order to promote the public health and welfare and the productive capacity of our Nation's population.

The complexities of environmental problems originate ins the deep interdependent relationships between the various physical and biological segments of man's natural and social world. Solutions to these environmental problems require an integrated program of research and development using input from a number of disciplines. The Health Effects Research Laboratory, Research Triangle Park, NC and Cincinnati, OH conducts a coordinated environmental health research program in toxicology, epidemiology and clinical studies using human volunteer subjects. Wide ranges of pollutants known or suspected to cause health problems are studied. The research focuses on air pollutants, water pollutants, toxic substances, hazardous wastes, pesticides, and non-ionizing radiation. The laboratory participates in the development and revision of air and water quality criteria and health assessment documents on pollutants for which regulatory actions are being considered. Direct support to the regulatory function of the Agency is provided in the form of expert testimony and preparation of affidavits as well as expert advice to the Administrator to assure the adequacy of environmental regulatory decisions involving the protection of the health and welfare of all U.S. inhabitants.

This report is a detailed engineering description of the major radiofrequency radiation exposure facilities used by the Experimental Biology Division in conducting radiofrequency health effects research. Readers of this report are encouraged to inform the Health Effects Research Laboratory of any omissions or errors. Comments or requests for further information are also invited.

F.Gordon Hueter,Ph.D.
Director
Health Effects Research Laboratory

CONTENTS

Forward iii

Abstract v

Acknowledgments vi

1. Introduction 1-4

2. 100 MHz Exposure Facility 5-13

3. 2450 MHz CW Exposure Facility 14-17

4. 2450 MHz AM Exposure Facility 18-27

5. X-Band Exposure Facility 28-30

Summary 31

References 38

ABSTRACT

This report describes the multi-user radiofrequency radiation exposure facilities for bio-effects research in use at the Health Effects Research Laboratory, Research Triangle Park, N.C. Four facilities are described: (1) a 100 MHz CW exposure system, (2) a 2450 MHz CW exposure system, (3) a 2450 MHz AM exposure system, and (4) an X-band pulsed RF exposure system. The individual facility descriptions include construction details, specifications, photographs, circuit drawings and block diagrams. All of the facilities incorporate environmental control systems and three have RF power-level regulation.

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The construction of these facilities would not have been possible without the capable efforts of Mr. Franklin Pendleton, Mr. Gordon Wharren, and Mr. Ralph Baudendistel who performed the structural design and construction for all these facilities. We also thank Mr. Walter Kozel and Mr. E. Baker Bailey for their work in the design and construction of the electronic circuitry.

INTRODUCTION

One of the missions of the Environmental Protection Agency is to investigate the effects of radiofrequency radiation (RFR) exposure on biological organisms. The EPA has been involved in this effort since its creation in 1970. This report focuses on the major RFR exposure facilities in use by the Health Effects Research Laboratory at the Research Triangle Park, N.C.

The operating frequency of an exposure system determines to a large degree the types of exposure systems that can be employed. For example transverse electromagnetic mode transmission lines (TEM cells) are generally not useful above approximately 1 GHz because of the small size required to prevent the propagation of unwanted higher order modes. Likewise, anechoic chambers become impractical and expensive below about 400 MHz because of the large size of the anechoic material and the chamber itself. Selection of the operating frequency generally results from one of two motives: (1) a facility is designed to simulate some environmentally occurring exposure situation over some narrow portion of the RF spectrum, or (2) an exposure system is designed which maximizes the chance of observing an effect based on a theoretical model and therefore the research leads to a better understanding of the mechanisms of interaction.

Four exposure facilities are described in this report. Each is a large, multi-animal exposure system available to all the research staff who quite frequently design multidisciplinary studies with these facilities. All of these systems are located in the same "high-bay" room which has been equipped with an auxilliary air conditioning system to precondition

the air. The first facility constructed was the 2450 MHz CW exposure system. 2450 MHz has become the defacto reference frequency in biologic effects research. Probably more work has been done at this frequency than at any other and most laboratories that are involved in this research have or have had a facility at this frequency. This happened largely for three reasons: (1) the availability of relatively low cost, high power RF sources since 2450 MHz is an ISM band frequency (An ISM band frequency is one of a number of frequencies reserved for use by the industrial, scientific and medical communities by the F.C.C.); (2) the excellent coupling of this frequency to laboratory animals and (3) the projected explosive growth in sales of microwave ovens possibly leading to the exposure of a significant portion of the population to low-level radiation.

The X-band exposure facility, which became operational in 1974, was designed to simulate the RFR generated by radar systems. Acquisition, naval ship, aircraft and small marine radars all operate in the 8.5 to 9.6 GHz range covered by our system. The first from the list above was the primary consideration motivating the design of this facility. At this high frequency, depth of penetration of the RF energy into a biological target is poor; however these frequencies are in extensive use in the environment and the system provides a tool to investigate the effects of high peak to average power ratio fields on biological organisms.

The 100 MHz exposure facility was designed to provide an irradiation facility in the environmentally significant FM band of radio frequencies. Radiation from these sources is deliberately beamed toward population centers for use in FM radiobroadcasting and is one of the more significant sources

of manmade RFR in human exposures [1]. This, coupled with research studies showing the resonance of the human body lies in the FM band [2], were strong arguments for EPA to examine frequencies in this band for potential biologic effects.

The 2450 MHz AM facility was constructed for several purposes: (1) EPA agreed to investigate for the Department of Energy the biological impact of the use of solar power satellites which would collect solar energy using satellites in geosynchronous orbit, convert this energy to microwave energy at a frequency of 2450 MHz and beam it down to earth to be collected by large arrays of antennas, (2) studies were published reporting effects with low-level amplitude modulated RFR. Because virtually all of the U.S. population is exposed to low-level amplitude modulated RFR, the EPA has been interested in these reports.

The systems used for RFR biologic effects studies are largely custom designed to tailor the system characteristics for the special needs of biologic effects research. A prime example of this is the power level stability of RF sources. In most commercial medium and high power RF generators and amplifiers, the RF power output is seldom regulated. The usefulness of an airport radar or an industrial microwave oven is not seriously compromised if the RF power output drifts by 10 to 20%. However, such a drift is of obvious concern in biologic effects studies since the absorbed energy is directly related to the stability of the RF source. Other features that are important in the design of RFR exposure facilities are: (1) provisions for environmental control, (2) spectral purity of the RF source, (3) personnel safety, (4) provision for automatically timed exposures and (5) RF field uniformity. The latter has become less important

in recent years as the state of the art has advanced both in the determination of whole body specific absorption rate (SAR) and localized SAR. As more becomes known about the effects of low-level amplitude modulated RFR, control of the spectral purity of test generators may grow in importance. For this reason we have tried to characterize the spectral content of the sources used here where possible.

100 MHz Exposure Facility

In the spring of 1976 a requirement was generated to develop an in-house exposure facility capable of irradiating large numbers of rodents at a frequency within the commercial FM broadcast band, 88-108 MHz. Measurement data that had been collected by EPA's Office of Radiation Program (ORP) showed that the greatest contribution to environmental levels of radiofrequency radiation to which the general population is being exposed is generated by FM band broadcast sources. In order to determine whether any potentially adverse biological effects of prolonged exposure to FM band radiofrequency energy exists, an EPA research task was undertaken which involved chronic exposures of rats at an RF frequency within the FM band arbitrarily selected to be 100 MHz [3].

The principal component of this exposure facility consists of a TEM-mode transmission line of rectangular co-axial cross section (Crawford Cell) [4]. The facility was designed to expose a total of 20 rats, divided equally on both sides of the line's center conductor. The exposure area where the animals are located is accessed by means of two doors in the outer walls of the exposure chamber. The line is energized by a 1 KW linear amplifier together with a 50 W driver source; power limitations of the components located in the RF transmission line which feeds the exposure cell, place an upper limit of 500 watts on the allowable forward power in the system. This provides a maximum power density in the line of just under 50 mW/cm^2 giving a whole-body-averaged SAR within the exposed rat of approximately 2 W/kg, as measured using twin-well calorimetry.

The biology experiments dictated that a sham chamber be provided in which control animals are housed under essentially conditions as those irradiated in the exposure chamber. The air temperature and humidity in both exposure and sham chambers are controlled within certain limits by a onepass environmental control system which feeds air through ducts into one end of both chambers. The air is subsequently exhausted into the room at the other end of the chambers. Figure 1 illustrates the complete exposure system, showing the TEM-mode exposure chamber at top center and the sham chamber at bottom right. The environmental control system is on the left with the high power RF amplifier beneath this equipment. Each of the component parts of the system will now be described in further detail.

Design of TEM-mode Transmission Line

The line was designed for a 50 ohm characteristic impedance, using design criteria provided by Weil [5]. The chosen cross sectional dimensions of the line are shown in the bottom left insert to Figure 2. In order to assure reasonably good field uniformity across the center conductor, the ratio of outer conductor dimensions was chosen to be a/b = 1.5. Proper TEM mode operation at 100 MHz dictated values of a = 114.3 cms (45") and b = 76.2 cms (30") for the outer rectangle dimensions. Using Gruner's criteria [6], the first TE_{01} higher order mode will begin to propagate at a frequency of approximately 104 MHz, thereby ensuring purely TEM mode operation at 100 MHz. For a 50 ohm impedance value, a value of w/b = 1.16 is required thereby setting the center conductor width at w = 88.4 cms (approximately 34 3/4"). The length of the transmission line was selected to be about a wavelength long at the 100 MHz operating frequency (i.e. approximately 3 meters or 10 feet).

The power P in watts needed to establish a power density value of 'p' mW/cm^2 at the point labeled 'X' in the bottom left insert of Figure 2, midway across the center plate and midway between center conductor and ground plane, is given by

$$P = 10.823p$$

Construction of Exposure and Sham Chambers

The mechanical design and fabrication of both the exposure and sham chambers were performed in our laboratory. Both chambers were constructed using type 6061-T6 aluminum plate of 3.18 mm (1/8") thickness with type 6063-T6 aluminum angle, 2.54 cms (1") wide and 3.18 mm (1/8") thick. The plates are held together at the corners by means of the aluminum angle which is fastened to the plates using 3.18 mm (1/8") pop rivets spaced approximately every 3" (7.62 cms).

Exposure Chamber

Figure 2 shows an assembled isometric view of the Crawford irradiation chamber, which stands in a vertical configuration. It is composed of three basic parts comprising the center section and the two pyramid shaped end pieces. The sides of the center section are formed of aluminum plate in which large holes were cut for the two access doors as well as two windows that are located in the wide side of the outer rectangle, parallel to the center plate. Both windows are covered with a 140 cms (20") x 100.3 cms (39 1/2") piece of perforated aluminum sheet [3.18 mm (1/8") holes separated by 4.76 mm (3/16"), 1.59 mm (1/16") thick] that is pop riveted to the wide sides of the center section. In addition, the windows are covered with 0.3 cms thick transparent acrylic sheet in order to prevent the environmentally conditioned air from escaping

out the windows. The doors, which are 140 cms (20") x 68.6 cms (27") in size, also contain 35.6 cms (14") x 53.3 cms (21") windows covered on the inside of the door with the same perforated aluminum sheet. The door windows are needed to allow for entry and exhaust of the environmentally conditioned air to and from the exposure area. The doors are hinged at their base to the narrow sides of the center section using long piano-type hinges and are held in their closed position by means of catches commonly used to secure sliding windows. Lengths of finger contact strips (#97-520-A, Instrument Specialties Co., Little Falls, NJ) were installed around the door opening in order to improve the RF seal of the closed doors with consequent reduced RF leakage. Lengths of 1" x 1" x 1/8" angle surround both ends of the center section (see Figure 2) in order to enable the two pyramidal end pieces to be mated to the center section, during final assembly.

The pyramid shaped end pieces consist of four triangle-shaped plates held together, as before, by lengths of aluminum angle; the pyramids are 30" (76.2 cms) in height. Lengths of 1" x 1" x 1/16" aluminum angle were installed around the large end (or base) of both pyramids and the tabs bent up in order to lie flush against the identical angle strips attached to the center section (see Figure 2). An insert in the top left of Figure 2 shows the apex of the pyramid end in enlarged detail. Note that a space is left on one side to allow for access to the interior for purposes of making electrical connections to the center conductor during final assembly. This space is subsequently covered by a removable inspection plate. The open end is covered by an assembly in which a UG-58A coaxial panel connector is mounted; this assembly is secured directly to the pyramid sides (see insert of Figure 2).

Prior to final assembly, all mechanical joints in both the center section and the pyramid ends were heliarc welded in order to reduce the leakage of RF energy from the structure. This included welding the perforated sheet used in the windows onto the surrounding aluminum plate of the sides and doors. During final assembly, the center plate is mounted in its correct position and held in place by means of 10.2 cms (4") thick foamed polystyrene support blocks four on each side of the center plate (see Figure 3). The two sets of support blocks immediately adjacent to the exposure area perform the additional function of thermally insulating the exposure area and limiting the volume of air whose temperature and humidity is to be controlled. The foam blocks are held in place using silicone rubber adhesive. A 2.54 cms (1") diameter, 80 cms (31.5") long fiberglass rod is then mounted through the middle of the center section (see Figure 2), in such a way that it passes through the center plate and is anchored on both wide sides of the center section. The purpose of the fiberglass rod is to support most of the center plate weight when the whole exposure assembly is placed in its normal upright position. The two pyramid end pieces are then mounted in place and mated to the flanges of the center section. At this point, a length of 1/16" x 1" Ferrex EMI gasket strip (METEX Corp., Edison, NJ) is placed between the flanges of each section for purposes of further reducing RF leakage. A specially built stand, previously constructed of 2" x 2" x 1/8" aluminum angle, was then added to the bottom end of the assembly and mated to the lower center section flange. The whole assembly was secured using 1/4"-20, 3/4" long screws with nuts spaced every 3" that pass through the flanges. Finally, the coaxial connector assembly is mounted at both apex ends of the assembled structure and the connectors then attached to both ends of the center conductor using wire and 3/16" pop rivets (see insert to Figure 2).

Sham Chamber

This is illustrated in Figure 3. It was designed to duplicate as closely as possible the environment in which the exposed animals are housed in the irradiation chamber. Consequently the length and width of the sham box is the same as the cross sectional dimensions of the exposure chamber and the sides of the sham box duplicate exactly those on the irradiation chamber in the region where animals are exposed, including the doors and windows. However, for the sham animals it is not necessary to duplicate the entire length of the exposure chamber, so that the height of the sham box was limited to 22 1/2". This allows for sufficient space to install 2" thick styrofoam blocks in both floor and ceiling of the sham box giving the identical 18 1/4" vertical spacing between styrofoam blocks that exists in the exposure chamber area. Aluminum panels (1/8" thick) were added to the top and bottom of the sham box for purposes of improving the mechanical rigidity of the overall assembly. A vertical plate which appears to divide the sham box into two compartments serves to simulate the presence of the center conductor. No welding of joints was required for the sham box.

RF System

A block diagram of the RF equipment used to excite the irradiation chamber at 100 MHz is shown in Figure 4. The system consists basically of a 1 kW linear class A amplifier (model 10270 with a model 11143 cavity plug-in, MCL, Inc., LaGrange, Ill) that is driven by a 50 Watt RF power generator (model 15022 with a model 6048 cavity plug-in, MCL, Inc.). RF frequency is monitored with a frequency counter (Hewlett-Packard model 5327A).

RF power is then fed via RG-214/U double shielded cable through a 100 MHz circulator/isolator (Addington Laboratories, Sunnyvale, CA) and a model 3020A bi-directional coupler (NARDA Microwave Corp., Plainview, N.Y.) to the irradiation cell which is terminated in a 600 W high power load (Bird Electronics, Cleveland, Ohio). The coupler is used to monitor the input power to the transmission line using a thermoelectric power meter (Hewlett-Packard model 435A, Palo Alto, CA). A 3.5 cms wide braided ground strap was used to tie the high power amplifier chassis to the irradiation cell and from there to outside ground rods. This was done for purposes of safety and to reduce RFI emissions.

A microwave power controller was designed for this system both to reduce the considerable amplitude drift exhibited by the 1 kW amplifier and also to provide a convenient means of controlling the start and duration of exposures. The timer portion of the controller provides a choice of digitally timed, delayed timed or manually controlled exposures. The controller offers the additional convenience of remote control of all the RF equipment thus simplifying system operation.

Figure 5 is a drawing of the RF leveling circuit in the microwave power controller. A reference signal is selected by the "power adjust" control which is compared to the "recorder output" signal provided by the microwave power meter. The amplified error signal from IC2 is fed to the modified power supply regulation circuits of the model 15022 RF power generator through IC4, an analog switch integrated circuit. The leveling circuit is disabled when the "manual" mode is selected. "Out of regulation" detection and display circuits are also provided.

The electric field distribution within the TEM cell was mapped using the fiberoptically linked EM field probe developed by the Bureau of Radiological Health [7]. Measurements were made in the absence of animals in the transverse plane in which test animals are located during irradiation. The transmission line was operated at a nominal 50-W input level and power density values were recorded at locations every 5 cm along both the X and Y axes in the region where test animals were located. Figure 6 shows a contour plot of these measurements; each contour represents a line of constant power density ranging between 2 and 20 mW/cm^2. Approximately 75% of the cross-sectional area shown is estimated to be within $\pm$20% ($\pm$1 dB) of the reference value at the center location, X = $\pm$17.5 cm, Y = 0. It is readily apparent from Figure 6 that enhanced field concentrations do exist in a relatively small region near the edges of the center plate.

Environmental Control System

Temperature and relative humidity are controlled during irradiations in both the exposure and sham chambers. Cool air from a water-cooled air conditioner is heated electrically to the desired temperature and controlled using a time-proportioning controller as described by Ali [8]. Steam is then introduced into the mixing chamber to raise the relative humidity to 50%. Relative humidity (RH) is regulated using a 3-mode controller. Two 10-cm diameter insulated ducts distribute the conditioned air to the two chambers. The air is then exhausted into the room through the distal perforated access door. Temperature is sensed with a thermistor probe and relative humidity is sensed with a temperature-compensated Pope-type sulfonated polystyrene ac resistance grid. Both sensors are located in the sham-exposure chamber to minimize the effects of load variability.

The airflow measured at the air duct-chamber interface, using a thermoanemometer (Alnor Instrument Co., Niles, IL), is approximately 1.1 m^3/min for the 100 MHz exposure chamber and 1.6 m^3/min for the sham-exposure chamber. The reason for this difference is not known but may be due to an air-baffling effect caused by several bends in the air duct leading to the exposure chamber. Both temperature and RH are monitored with a dual-channel strip chart recorder during irradiations.

2450 MHz CW Exposure Facility

The 2450 MHz CW microwave exposure facility is a free-space anechoic chamber for whole body irradiations (Figures 7 and 8). The anechoic chamber, which is 3m x 3m x 4.5m high, is constructed with Emerson and Cuming CV-CB-24 floor blocks and CV-B-24 wall blocks. These blocks have a maximum reflectivity of approximately 34dB at 2.5 GHz. The RF power is supplied by a Varian Associates Model PPS 2.5AS microwave generator which is rated at 2.5 kw minimum. Because this generator has an unregulated power supply, a microwave power controller was designed [9] to compensate for drift in RF output due to line voltage fluctuations and temperature changes. With the controller, line regulation has been improved to 0.1% for a $\pm$10% change in line voltage and the temperature coefficient of RF output is 0.1%/°C. The controller also has several convenience features such as digital readout of radiated power, a built in digital timer to control length of exposure and power level control over a 30 to one range. The controller will also accept both a remote setpoint signal and on/off control signals, and also provides a recorder output signal proportional to radiated power. With the use of a directional coupler and water-load assembly, regulated power densities between 1 $\mu W/cm^2$ and 200 mW/cm^2 are available.

Although the generator produces a CW output at all operating levels, measurement of the detected RF output revealed the presence of some ripple. This ripple waveform contains the 60Hz line frequency plus its harmonics. The output of a crystal detector sampling a portion of the RF power was fed into a wave analyzer to obtain a measure of the spectral content of the ripple (Table 1) and the total RMS ripple.

Table 1

Spectral Content of Generator RF Output Ripple

Freq (Hz)	Voltage (mV,RMS)	Freq (Hz)	Voltage (mV,RMS)
DC	80	300	0.2
60	1.0	360	3.0
120	8.2	600	3.0
180	0.4	720	0.4
240	1.2		

These measurements were performed with the generator operating at 1KW. The total RMS ripple of the generator was 11%. It should be noted that these measurements were taken after the installation of a full wave bridge in the filament circuit of the generator. The full wave bridge significantly reduced the total RMS ripple by reducing the 60 and 120 Hz components.

The microwaves are fed into the anechoic chamber through a Scientific Atlanta Inc. 10dB pyramidal horn antenna near the top of the chamber. The 10dB antenna provides a broad beam width and more uniform field at shorter distances than would be available with a higher gain antenna. It is readily apparent that an overhead antenna greatly facilitates multiple animal exposures since all animals can be placed on a horizontal plane.

The animals are placed in a foamed polystyrene animal exposure chamber with interior dimensions 76.2 x 76.2 x 61 cm wide. This chamber is constantly flushed with environmentally controlled air and can be raised or lowered by virtue of the bellows type ducting as necessitated by power density requirements.

The metal-free ducting in the anechoic chamber is made of a neoprene coated nylon fabric. The animal exposure chamber is also equipped with fiber optics "house lights" to avoid the scattering from wires. The "house lights" are variable in intensity and can be remotely programmed. A similar sham exposure chamber is located adjacent to the anechoic chamber.

Environmentally controlled air is fed through insulated ducts to the animal exposure chamber and sham chamber from a specially designed environmental control system which is located adjacent to the anechoic chamber. Range of temperature control is from -10°C to +40°C; the range of humidity control is from 20% to 80%. Air temperature and relative humidity inside the sham chamber are displayed on digital panel meters. Both temperature and relative humidity are regulated using three-mode proportional controllers. Air velocity is measured with a hot wire anemometer. Based on measured duct air velocities, wind speed in the animal and sham exposure chambers can be adjusted from 5 to 10 m per minute.

Densitometry and Dosimetry

Fields are measured using a in-house built diode detector near field dipole probe constructed as shown by Swicord [10]. The detector is a hot carrier diode (HP 5082-2800) and the DC signal is measured outside the anechoic chamber through lengths of virtually RF transparent high impedance resistive lines. The dipole probe has been calibrated from 4 $\mu W/cm^2$ to 25J mW/cm^2 and has been in use for eight years. The probe has shown excellent long term stability and durability. A three element version with linearized readout has recently been constructed for use in this exposure facility.

Accurate description of the exposure situation as well as measurement of the RF field allows other researchers to at least duplicate experiments and verify results but without knowledge of thermalized dose to the animal. Questions arise when only densitometry is used whether each animal in an exposure array is receiving the same dose. To resolve these deficiencies, capability for whole body dosimetry was developed in our laboratory [11]. The technique used is that of twin-well calorimetry described by Hunt and Phillips [12]. Several calorimeters have been constructed of different sizes to accomodate different size animals and are now in routine use in our laboratory. The twin-well calorimeters have been interfaced to a microcomputer which automates data collection as well as greatly reduces the typical 12 hour time required for the wells to reach thermal equilibrium.

2450 MHz AM Exposure Facility

The 2450 MHz AM system (Figures 9 and 10) is a free-field anechoic chamber type facility with an oscillator-amplifier chain microwave generation technique. This system shares the anechoic chamber and environmental control system used in the X-band exposure facility which is described elsewhere in this report. System specifications are listed in Table 2.

A block diagram of this facility is shown in Figure 11. The heavy black lines indicate the main RF signal path from source to antenna. A good overview of the system can be gleaned by examination of the block diagram. The cavity oscillator is an Englemann Microwave Co., Montville, N.J., Model CC-24 tuneable, 100 mW CW cavity oscillator capable of operating from 2.0 to 4.0 GHz. The oscillator power output is divided into two equal portions with the splitter. The portion going to the wavemeter, a PRD Electronics Div., Syosset, N.Y., Model LS-518, is used for setting the RF frequency. The remaining portion is fed to two PIN diode attenuators (General Microwave Corp., Farmingdale, N.Y., Model D 1952). The first unit is used to amplitude modulate the carrier frequency while the second unit is used to level the RF power applied to the antenna. The next system component in the chain is a Logimetrics Inc., Plainview, N.Y., Model A100/S one watt TWT amplifier which has an operating frequency range of 2.0 to 4.0 GHz. The TWT amplifier functions as an intermediate power amplifier to provide the power required to drive the high power amplifier which follows. The high power amplifier is an MCL Inc., LaGrange, Il., Model 10284 one kilowatt CW klystron amplifier using a 4K3SK klystron tube with a tuneable frequency range from 2.4 to 2.7 GHz.

The klystron has been broad-band tuned to provide maximum bandwidth and linearity. A 3dB bandwidth of 8.1 MHz was obtained with broadband tuning. Gain is compromized slightly by this tuning method but this is not troublesome because of the adequate drive capability available from the TWT amplifier.

The high power amplifier output is filtered with an RLC Electronics, Mt. Kisco, N.Y., Model F4341 low pass filter which has a 3.1 GHz 3dB cutoff frequency and at least 60dB attenuation at 5.0 GHz and above. The RF power is introduced into the anechoic chamber with a Nurad, Inc., Baltimore, Md., Model 24HC001 circularly polarized antenna. This antenna has a gain of 9.5dB at 2.45 GHz and is the device that imposes the smallest carrier frequency range on the system - 2.4 to 2.5 GHz.

Power is sampled with a 50dB waveguide coupler. A portion of the sampled power is fed to a Mini-Circuits Lab, Brooklyn, N.Y., Model ZLW-11HB double balanced mixer. The mixer is used for frequency conversion to bring the I.F. frequency into the operating range of the modulation meter. Local oscillator power is provided by an Englemann model HFE-4 2.0 GHz oscillator which when mixed with the 2.45 GHz frequency of the transmitted signal, produces an I.F. frequency of 450 MHz. The I.F. signal is low pass filtered with an RLC Model F-30-600-N filter to remove harmonics and intermodulation products. The modulation meter is a Racal-Dana Instruments Inc., Irvine, Ca., Model 9009. This meter has both an I.F. output at 500 kHz and an audio output. The I.F. output permits oscilloscope viewing of the modulation on a carrier frequency while the audio output provides the modulation signal alone.

The remaining power from the sample taken with the 50dB coupler is used to measure the level of the transmitted power. A Hewlett-Packard Co., Palo Alto, Ca., Model 435A microwave power meter with a model 8481A thermoelectric power sensor is used for this purpose. It is highly advantageous in this application to use a thermoelectric power sensor rather than a crystal detector type because this type of sensor will measure correctly a microwave signal with virtually any form of amplitude modulation. The recorder output signal from the power meter is used as the feedback signal for the leveling circuit.

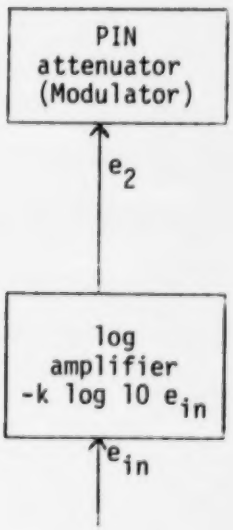
Modulation Circuits

Three modulation modes are provided: AM, Pulse and External (Figure 12). Two of these modes - pulsed and AM, use a PIN attenuator to modulate the carrier signal while external modulation is applied in the leveling circuit in which the external modulation signal is used as a pseudo reference voltage for the leveling circuits. The external mode is only used for modulation frequencies below 1 Hz. Pulsed modulation is formed by directly driving the modulator PIN attenuator with a pulse waveform from the function generator. The minimum pulse width with good wave shape is 200 nS which is imposed by the switching speed limitations of the PIN attenuator.

Sine Wave Amplitude Modulation

The desired response from the modulator PIN attenuator for ordinary AM is:

$$e_{in} \propto \frac{V_{RF\ out}}{V_{RF\ in}} \qquad (1)$$



However the PIN attenuator response is normally 10dB of attenuation per volt of control signal, e_2, ie:

$$10 \log \frac{P_{out}}{P_{in}} = -10\ e_2$$

Transforming this equation to more useful form we get:

$$e_2 = -\log \frac{P_{out}}{P_{in}} = \log \frac{P_{in}}{P_{out}}$$

$$e_2 = \log \left(\frac{V_{RF_{in}}}{V_{RF_{out}}}\right)^2 = 2 \log \left(\frac{V_{RF_{in}}}{V_{RF_{out}}}\right)$$

The log amplifier, an Analog Devices, Norwood, Ma., model AD755N, is used to linearize this relationship to the desired overall transfer function (eq 1). Choosing the coefficient, k, to be two we get:

$$e_2 = -k \log 10\, e_{in} = 2 \log \left(\frac{V_{RF_{in}}}{V_{RF_{out}}}\right)$$

$$\log 10\, e_{in} = \left(\frac{V_{RF_{out}}}{V_{RF_{in}}}\right)$$

$$10\, e_{in} = \frac{V_{RF_{out}}}{V_{RF_{in}}}$$

$$\text{or } e_{in} = \frac{1}{10} \quad \frac{V_{RF_{out}}}{V_{RF_{in}}}$$

Since neither the PIN attenuator nor the log amplifier obey the stated transfer functions exactly, some non-linearity will still be present in the overall transfer function and this will contribute to the total harmonic distortion (THD) of the system output. However the largest source of THD is the one kilowatt amplifier. This is discussed further below.

Auto-Bias Circuit

When operating with ordinary AM, a d.c. bias must be provided to the PIN attenuator so that the modulating waveform can cause the output to swing both above and below some reference level. Two adjustments are therefore required to set a desired modulation index: d.c. bias, and modulation waveform amplitude. If we assume that the gain of the TWT amplifier has been fixed such that the minimum attenuation settings of both PIN attenuators are required to produce a 1 kW output, then the peak of the modulating waveform should cause the modulation attenuator to reach minimum attenuation. This is achieved by proper choice of d.c. bias.

An auto-bias circuit has been designed which provides this function automatically. As the level control of the function generator is adjusted to set the desired modulation index (using the modulation meter), the auto-bias circuit adjusts the d.c. bias such that the maximum average power is produced for the specified modulation index. Figure 13 is a schematic of this circuit. IC 10 and 11 are a peak detector with a 0.0 to -5.0 Vdc output for a sine wave input of 0.0 to 10V peak to peak. If the input to the circuit is Asin (wt), the circuit provides the following output at IC 12, pin 10: V_o = (10 volts -A) +Asin (wt). IC 10 and 11 extract A, the amplitude of the sine wave. Part I.C. 12 computes (10V-A) and the 2nd half of IC 12 sums the input sine wave with the term (10V-A). Notice that for any value of A between 0.0 and 5V the peak value of V_o is always 10V. The frequency range of operation of this circuit is from 1.0 Hz to 10 kHz. The lower frequency limit is due to the finite values of the three capacitors while the high frequency response is limited by pin attenuator. Operation between 1 Hz and 10 Hz can only be performed with the leveling circuit disabled because the feedback loop cannot distinguish between the modulation signal and an error signal. Above 10 Hz the power sensor does not have a fast enough response time to detect the modulation and hence the modulation is not treated as a disturbance.

Leveling Circuits

The leveling circuits can be understood by examination of Figures 11 and 12.

The leveler is useful for a variety of reasons. In field mapping applications much time is saved by simply pushing a start button to reproduce a power density rather than turning a dial and waiting for the generator to stabilize. As long as the power adjust dial is left undisturbed the same average output power will be produced every time the system is restarted.

Most high-power amplifiers do not have regulated power supplies. The most obvious advantage of a leveler is to prevent drifts in RF power due to several sources such as line voltage fluctuation and thermally induced drift.

The controller operates by comparing a feedback signal from the recorder output terminal of the microwave power meter, which is sampling the transmitted RF power, to a dc voltage derived from a stable reference diode. The comparison is performed in IC 1 and the error signal is both displayed on a milliammeter and fed to the integrating amplifier, IC 2. Integral control is used because no average error is produced with this form of controller. The integrator output is then fed to a log amplifier to insure a linear relationship between the integrator output voltage and the output of the leveler PIN attenuator. IC 6 performs these control functions: (1) the milliammeter is disconnected when the RF is off, (2) a bias voltage is applied to the integrator so when the RF is switched on, the RF output will ramp up from zero (3) the "out of regulation" lamp is disabled and (4) the cavity oscillator is disabled.

IC 7 is an analog switch which in conjunction with the microwave power meter matches the operating range and sensitivity of the power

meter to the range and sensitivity of the leveler. This arrangement permits the accurate setting of very small powers while preserving system stability. A spare wafer-switch section on the power meter range selector is used to sense which range the power meter is on. The appropriate bias voltage, either 0.0, 1, 2 or 3V, is then switched through the analog switch and summed with the error signal at IC 5.

IC 8 and associated components monitor the integrator output voltage. The normal operating range is between +100 mV and +10V. If a voltage outside this range is sensed, the "out of regulation" lamp will light.

In the manual mode of operation, the feedback path is blocked and the level attenuator is controlled directly by the power adjust potentiometer through IC 5.

Control and Timing Function

The system can operate either manually controlled, automatically timed or automatically delayed and timed. The digital timer has a resolution of one second and can be set for exposures and/or delays of up to 99 hours 59 minutes and 59 seconds. The timer has 1 MHz crystal oscillator time base. Two banks of thumbwheel switches are provided: one for setting the delay time, and the other for setting the exposure time. A six digit LED display indicates the elapsed time for both the delay and exposure times.

Total Harmonic Distortion

If a single frequency is applied to a perfectly linear amplifier, the output will contain only that frequency. If the actual amplifier contains some nonlinearity, a sine wave applied to its input will result

in an amplified version of the input plus one or more of the harmonics of the input frequency. Any amplifier becomes nonlinear as the output level approaches saturation and when this happens, many harmonics of the applied frequency are generated. Total harmonic distortion (THD) is a measure of the individual harmonic amplitudes relative to the amplitude of the fundamental frequency. THD is defined by the following equation:

$$\% \text{ THD} = 100 \times \frac{\sqrt{A_1^2 + A_2^2 + A_3^2 + .. A_n^2}}{A_f}$$

where A_n is the amplitude of an individual harmonic and A_f is the amplitude of the fundamental. The following are typical values for various equipments:

High quality stereo amp.	0.1% THD
1 kW AM Transmitter (95% AM)	2.5%
50 kW AM Transmitter (95% AM)	3.0%

Bioeffects studies of sine wave amplitude modulated radio frequency radiation is an active research area at present. Several researchers are reporting low-level effects at specific modulation frequencies. Future work may indicate that knowledge of the spectral content of a waveform is necessary to explain experimental observations. For this reason Tables 3-7 are included which show the spectral content of the harmonic distortion as a function of operating power level, modulation frequency and percent of AM. The total harmonic distortion has been computed and is listed in the extreme right hand column of these tables.

The THD has also been plotted in Figure 14. At a transmitted power of about 200W, the THD is reasonable at all modulating frequencies and percent modulations. Higher power can be used if the percent of AM is kept low without causing excessive distortion.

Auto-Restart Capability

This system has provisions to restart an irradiation after a power failure has occurred and power has been restored. Critical components of the system are supported by an Uninterruptible Power Source (UPS) and those components that are supported in this way are designated by an asterisk in the system block diagram (Figure 11). Because of cost and size constraints, the 1 kW amplifier is not supported by an UPS; however this unit does have an auto-restart feature which automatically reactivates the amplifier after a power failure. If a delayed or delayed time exposure had been selected and a power failure occurred, the digital timer would stop counting for the period of time that the 1 kW amplifier was disabled due to the power failure. Elapsed time information would not be lost because the UPS supports these circuits during power failures. When line power is restored and the 1 kW amplifier has recycled to the on state, the digital timer would resume counting and the irradiation would resume. Optionally, the restart feature can be disabled by the experimenter, in which case any power failure will cause the irradiation to terminate permanently.

X-Band Exposure Facility

The X-band exposure facility (Figure 9 and 15) is a free-space anechoic chamber which operates over the range of 8.5 to 9.6 GHz. This system is designed to simulate radar exposures and as such is a pulsed source with a pulse repetition rate adjustable from 10 Hz to 6000 Hz. Within the constraints of a maximum duty cycle of 0.001, the pulse width is adjustable from 0.4 to 3.4 microseconds. Maximum average and peak power densities obtainable one meter from the 15dB gain horn antenna are 10 mW/cm^2 and 10 W/cm^2 respectively. At this distance the power density is uniform to within $\pm$10% in a 20 cm diameter circle.

The X-band anechoic chamber has interior dimensions of 2.7m x 2.7m x 2.6m high. Floor blocks are Microwave Control Products, Inc., Winchester, Massachusetts Model RFP-9 structural absorber and wall blocks are model FFP-5 and -8 pyramid RF absorber with the -8 type used in areas in the direct path of the antenna radiation.

Biological subjects are placed in a foamed polystyrene animal exposure chamber with interior dimensions 76.2 x 76.2 61cm wide. This chamber is constantly flushed with environmentally controlled air and can be raised or lowered by virtue of the bellows type ducting as necessitated by power density requirements. The metal-free ducting in the anechoic chamber is made of a neoprene coated nylon fabric. The animal exposure chamber is also equipped with fiber optics "house lights" to avoid the scattering from wires. The "house lights" are variable in intensity and can be remotely programmed. A similar sham exposure chamber is located adjacent to the anechoic chamber.

Environmentally controlled air is fed through insulated ducts to the animal exposure chamber and sham chamber from a specially designed environmental control system which is located adjacent to the anechoic chamber. Range of temperature control is from -10°C to +40°C; the range of humidity control is from 10% to 90%. Air inlet and outlet temperature is displayed as well as percent relative humidity. Both temperature and relative humidity are regulated using three-mode proportional controllers. Average air velocity in the sham and animal exposure chambers can be adjusted from about 3.0 to 10 m per minute.

A block diagram of exposure system is shown in Figure 16. Microwave power is generated by a Raytheon RK2J51 tunable pulsed magnetron rated at 40kW peak power. The tube is driven by a modified Applied Microwave Labs MH250 pulse modulator. The pulse modulator contains a built in adjustable pulse generator permitting control of pulse rate and pulse width over the ranges stated above. High voltage DC is supplied to the modulator by a Hipotronics, Inc. Model 820-50 power supply.

Although the modulator has a high voltage pulse output continuously variable from 0 to rated tube voltage, the RF output can only be reliably varied over a 6dB range because of inherent magnetron tube operating characteristics. To obtain greater power adjustment range, the waveguide switch network and associated components were included in the system. The lower path shown in Figure 16 is the high power range and is used from full power to 0.25 full power with the power supply high voltage control used for level setting. Below this power setting, the low range is selected and power is diverted through the 6dB coupler and then through the rotary vane attenuator. The rotary vane attenuator is adjustable over a 60dB

range. The high power range was included because of average power and cost limitations of commercially available rotary vane attentuators.

A portion of the available RF power is sampled with the 30dB coupler and used for peak and average power monitoring as well as for RF frequency selection and pulse width readout. The peak-detection circuit is needed because of the extremely low average value of the detector pulse output. An analog 50 microamp panel meter is used with the peak-detector circuit to indicate the null when the wavemeter is tuned. The pulse width readout circuit displays the pulse width directly in microseconds digitally and has a 10 nanosecond resolution.

Field intensity is measured using an in-house built diode detector dipole probe (Figure 17). The leads of the diode act as antenna elements and are cut to 2mm lengths. The DC signal developed across the diode is measured outside the anechoic chamber through lengths of virtually RF transparent high impedance resistive lines. Small holes are drilled in the semiconducting line and then slipped over the diode leads which are coated with a small amount of conductive epoxy. The diode used is a HP 5082-2303 Hot Carrier Diode. The semiconducting lines are routed through an acrylic tube. The diode and a small portion of the acrylic tube is encapsulated with a foamed polystyrene sphere. The probe operates from 1 $\mu W/cm^2$ to 10 mW/cm^2 and has been calibrated only at a generator duty cycle of 0.001. With a 1 megohm terminating resistor temperature coefficient of the probe is about 1%/°C.

SUMMARY

The multi-user radiofrequency radiation exposure facilities for biologic effects research at the Health Effects Research Laboratory, Research Triangle Park, N.C. have been described. These facilities are: (1) the 100 MHz CW exposure system, (2) the 2450 MHz CW exposure system, (3) the 2450 MHz AM exposure system, and (4) the X-band pulsed RF exposure system. The control and characterization of variables of particular concern to researchers in the RFR area have been highlighted. These include power-level stabilization, environmental control, timing functions, spectral purity and field uniformity.

TABLE 2

SPECIFICATIONS: 2450 MHz AMPLITUDE MODULATED EXPOSURE FACILITY

System Type	Free Field in Microwave Anechoic Chamber
Freq. (RF)	2.4-2.5 GHz
Field Characteristics @ 130 cm	
Power Density	40 mW/cm^2
Polarization	Circular or Linear
Axial Ratio (circ. pol.)	1.8 dB Max.
Area of Uniform Field ($\pm$10%)	Circle with Dia. = 50 cm
Transmitted Power	1 kW
Modulation Capability	
AM - Sine Wave	1 Hz* - 10 kHz
Percent Modulation	0-95%
Pulse	
Min. Pulse Width	200 nS
Rise Time	100 nS
Fall Time	100 nS
Ext (power modulation)	DC - 1Hz
Other Features	
Amplitude Stabilization	Electronic Feedback Control
RF Frequency Monitoring	Cavity Wavemeter/Detector
Modulation Monitoring	Modulation Meter
Environmental Control System	
Temperature Range	-10° to +40°C
Humidity Range	10-90% RH
Dimensions (Anechoic Chamber)	2.7 x 2.7 x 2.7 m
Dimensions (Environmentally Controlled Styrofoam Animal Exposure Chamber)	76 x 76 x 61 cm

*Amplitude stabilization may not be used for modulation frequencies between 1 Hz and 10 Hz.

TABLE 3

50 W Transmitted Power										
Modulation Frequency	% AM	Harmonics 2nd	3rd	4th	5th	6th	7th	8th	9th	THD
30 Hz	10	-37dB	-56	-52	-60	-46	-52	-50	-42	1.8
	50	-37	-40	-58	-59	-58	-57			1.7
	90	-40	-46	-43		-50	-42	-57	-58	1.4
100 Hz	10	-34	-48	-42	-54					2.2
	50	-35	-41	-58						2.0
	90	-36	-48	-43		-52	-54	-56	-58	1.8
1000 Hz	10	-33	-54							2.2
	50	-32	-39	-58						2.8
	90	-29	-35	-42	-46	-45	-47	-52		4.1
10000 Hz	10	-37								1.4
	50	-31	-38	-56						3.1
	90	-22	-36	-44						8.1

TABLE 4

100 W Transmitted Power										
Modulation Frequency	% AM	Harmonics 2nd	3rd	4th	5th	6th	7th	8th	9th	THD
30 Hz	10	-34dB	-58	-50		-50	-50	-41		2.3
	50	-31	-37	-60	-56		-54			3.2
	90	-33	-39	-43	-54	-49	-51			2.6
100 Hz	10	-32	-54	-42						2.6
	50	-30	-37		-58					3.5
	90	-31	-40	-43	-52	-53	-52	-56		3.1
1000 Hz	10	-32	-52							2.5
	50	-28	-37	-59	-59					4.2
	90	-27	-34	-41	-47	-44	-46	-58		5.1
10000 Hz	10	-36	-48	-52						1.7
	50	-34	-35	-56						2.7
	92	-23	-33	-43						7.5

TABLE 5

200 W Transmitted Power										
Modulation Frequency	% AM	Harmonic 2nd	3rd	4th	5th	6th	7th	8th	9th	THD
30 Hz	10	-33dB	-60	-55	-60	-38	-51	-45	-44	2.7
	50	-26	-39	-58		-54	-56			5.1
	90	-25	-36	-48						5.9
100 Hz	10	-30	-46	-41	-56					3.3
	50	-26	-39	-58						5.1
	90	-25	-37	-48	-54	-56	-54	-55		5.8
1000 Hz	10	-30								3.2
	50	-25	-39	-58						5.7
	90	-23	-32	-40	-46	-45	-47	-50	-56	7.6
10000 Hz	10	-33	-50							2.3
	50	-34	-34	-56						2.8
	90	-24	-29	-43						7.3

TABLE 6

300 W Transmitted Power										
Modulation Frequency	% AM	Harmonic 2nd	3rd	4th	5th	6th	7th	8th	9th	THD
30 Hz	10	-29dB	-58	-53	-60	-42	-47	-43		3.7
	50	-23	-41	-60	-58	-57				7.1
	90	-21	-36	-58	-59	-53	-54			9.1
100 Hz	10	-30	-47	-42	-57	-60				3.3
	50	-24	-41	-55						6.4
	90	-22	-38	-56	-57	-55	-54	-57		8.1
1000 Hz	10	-29								3.5
	50	-23	-40	-55	-64					7.2
	90	-20	-32	-38	-44	-44	-46	-52		10.4
10000 Hz	10	-33	-50							2.3
	50	-30	-34	-57						3.7
	90	-25	-26	-42	-64	-60				7.6

TABLE 7

500 W Transmitted Power										
Modulation Frequency	% AM	Harmonic 2nd	3rd	4th	5th	6th	7th	8th	9th	THD
30 Hz	10	-28dB	-50	-50	-60	-38	-42	-36		4.6%
	50	-18	-38	-52	-56					12.7
	90	-15	-35	-47	-60	-46	-51			17.9
100 Hz	10	-26	-48	-42						5.1
	50	-18	-39	-52						12.6
	90	-14	-38	-47	-57	-48	-49			20
1000 Hz	10	-26								5.0
	50	-18	-38	-51						12.7
	90	-14	-28	-32	-38	-38	-42			20.6
10000 Hz	10	-29	-52							3.6
	50	-22	-31	-54	-60					8.4
	90	-21	-20	-36	-43	-54				13.5

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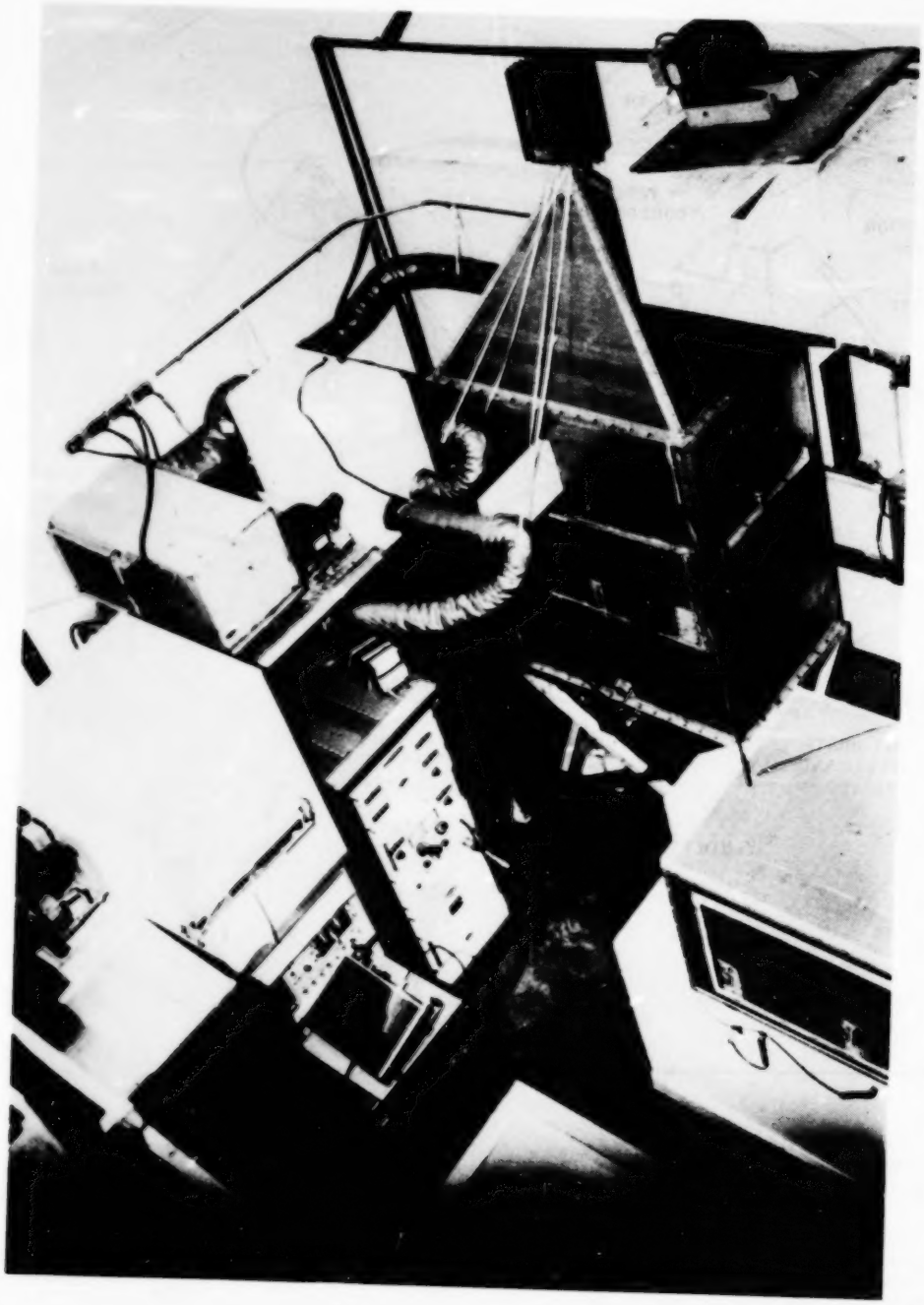


Figure 1. Overall views of the 100 MHz exposure facility. The rectangular strip transmission line chamber is at top right and the sham chamber is in the right foreground. The 1 kW RF amplifier is at left center, beneath the environmental control equipment.

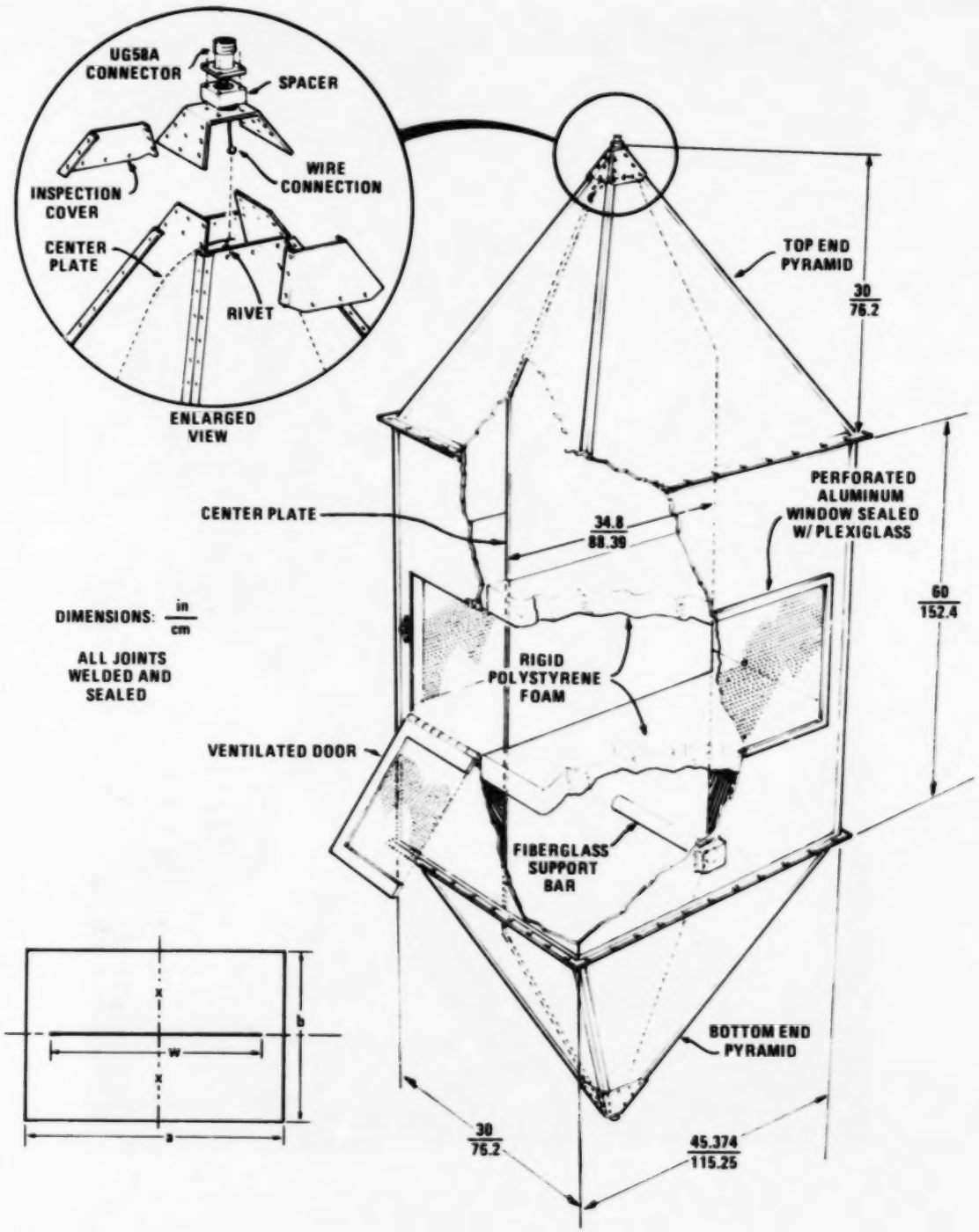


Figure 2. Isometric view of the rectangular strip-transmission line exposure facility (Crawford Cell).

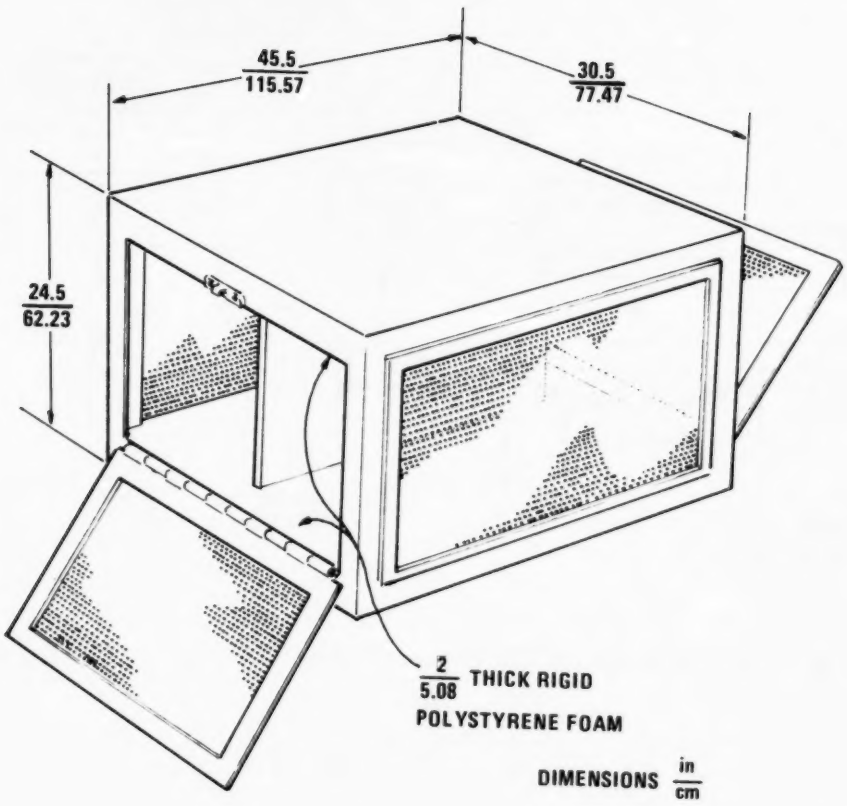


Figure 3. Isometric view of the sham chamber.

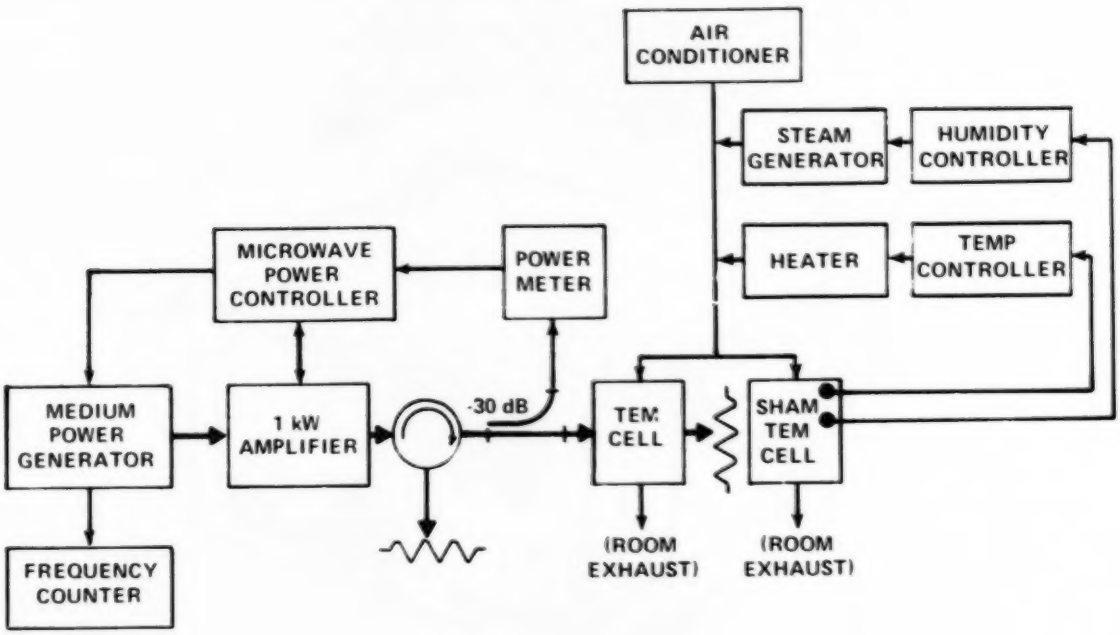


Figure 4. Block diagram of 100 MHz exposure facility.

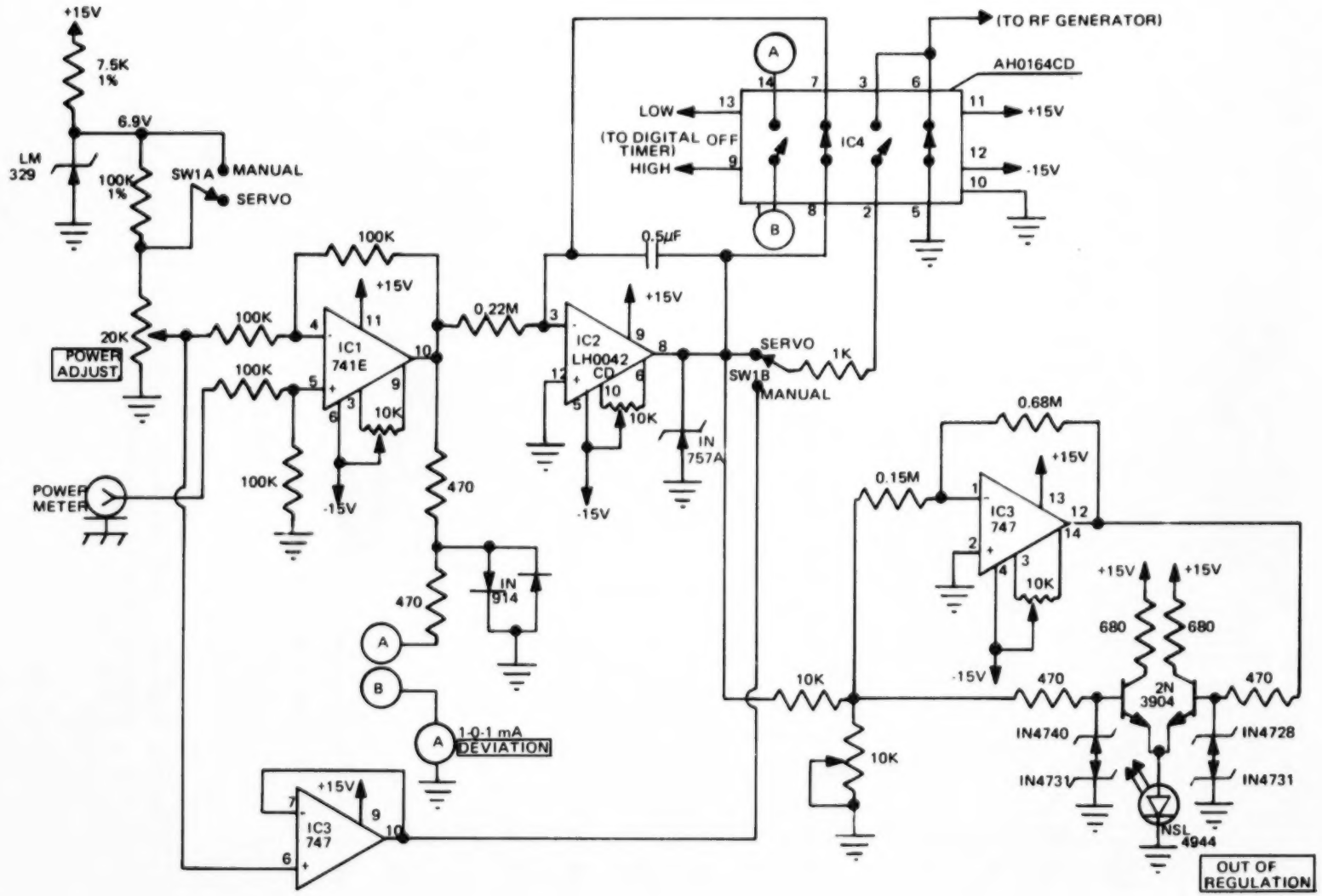


Figure 5. RF leveling circuit in the 100 MHz exposure system's microwave power controller.

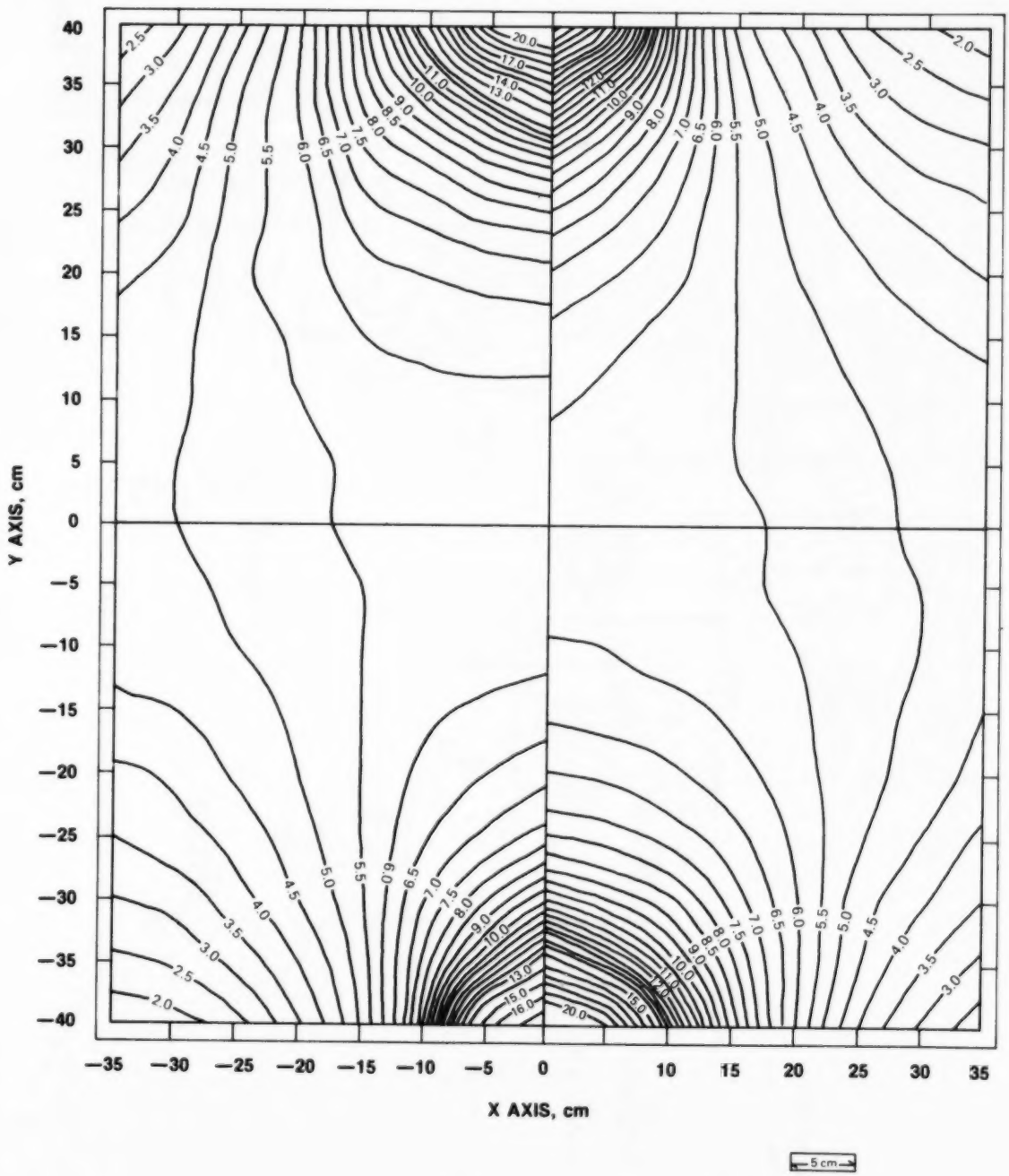


Figure 6. Internal cross-sectional field map of exposure are showing contours of constant power density in mW/cm^2 (50 W input).

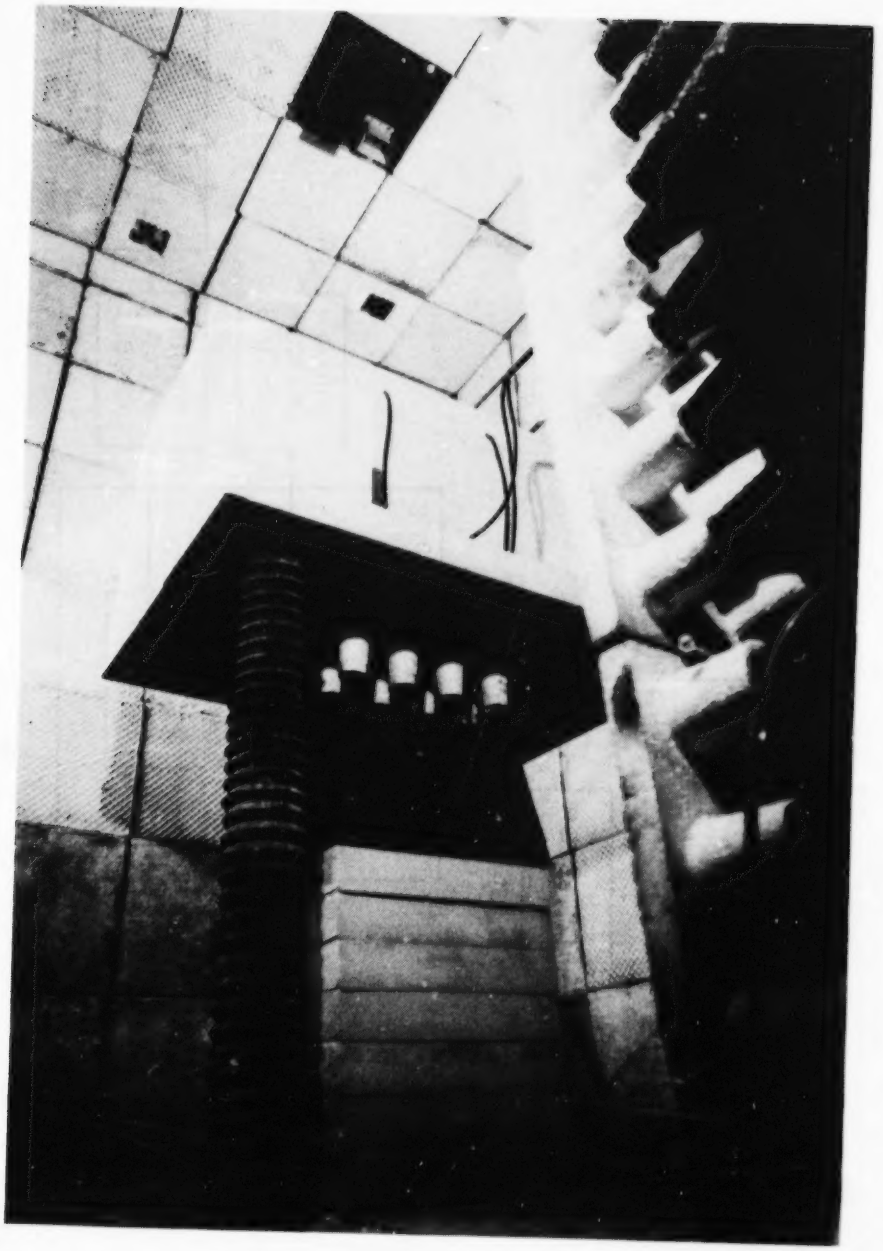


Figure 7. 2450-MHz CW microwave exposure facility.

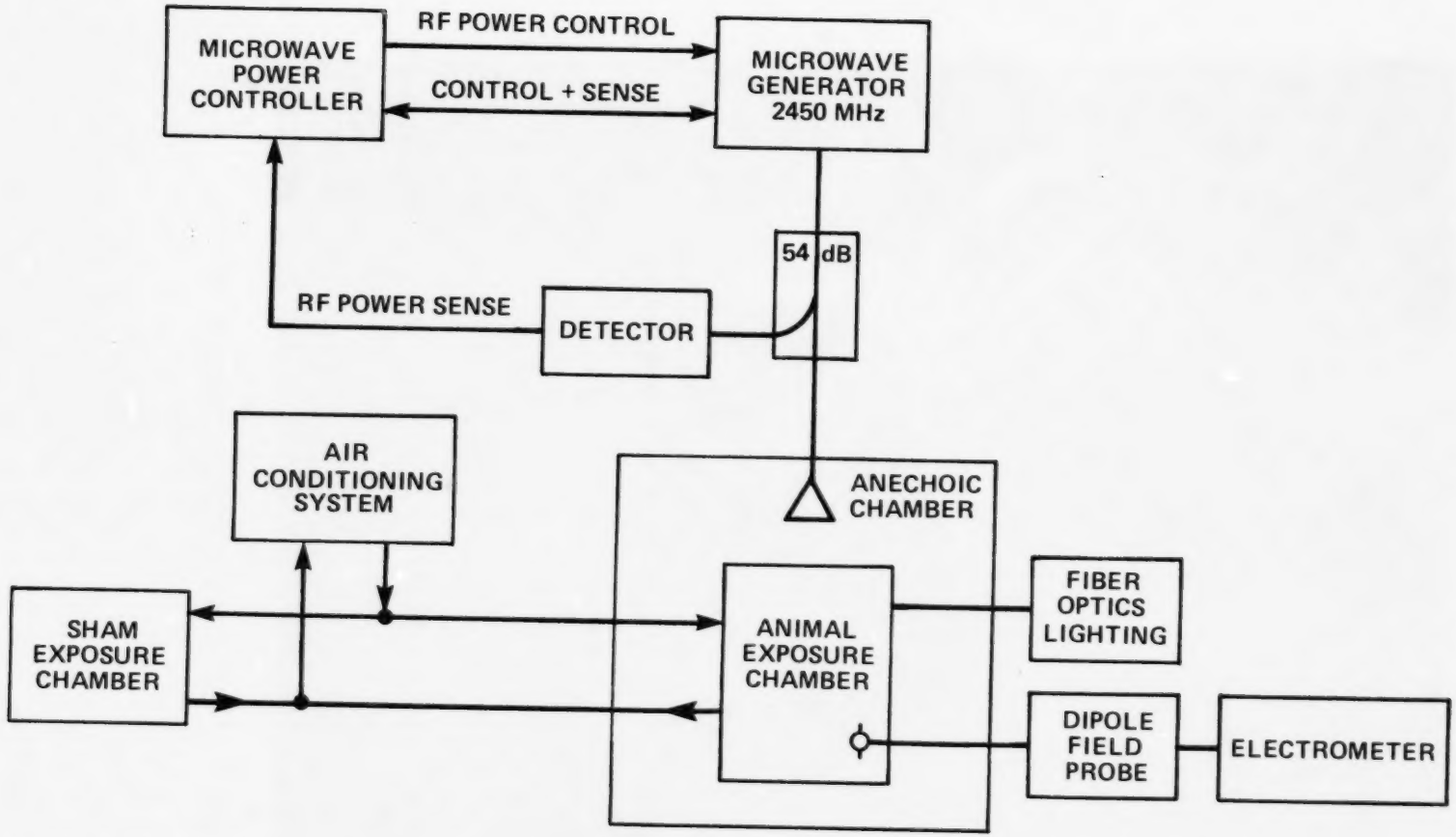


Figure 8. Block diagram of the 2450-MHz exposure facility.

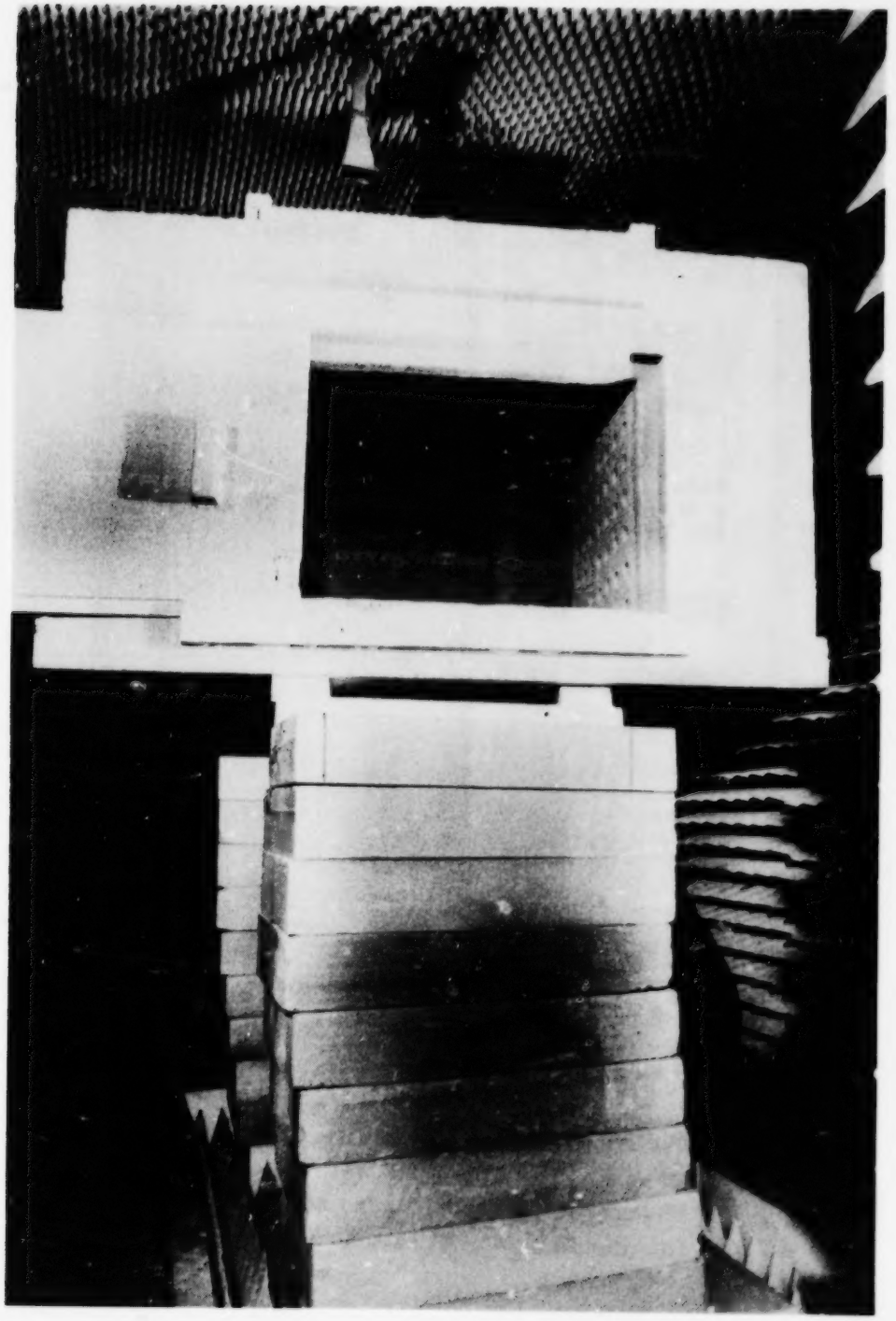


Figure 9. Anechoic chamber used for both the 2450-MHz AM and the X-band exposure facilities.

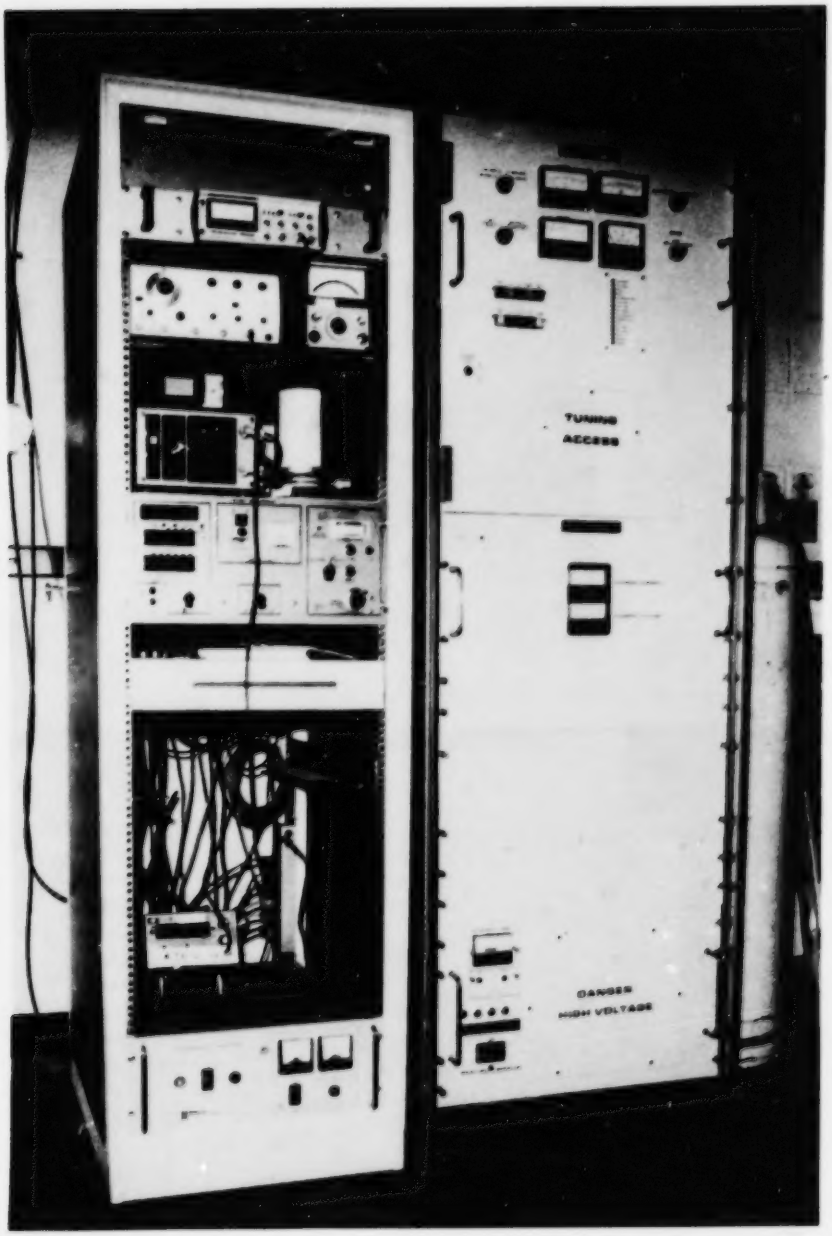


Figure 10. RF generation, control and modulation equipment for the 2450 MHz AM exposure facility.

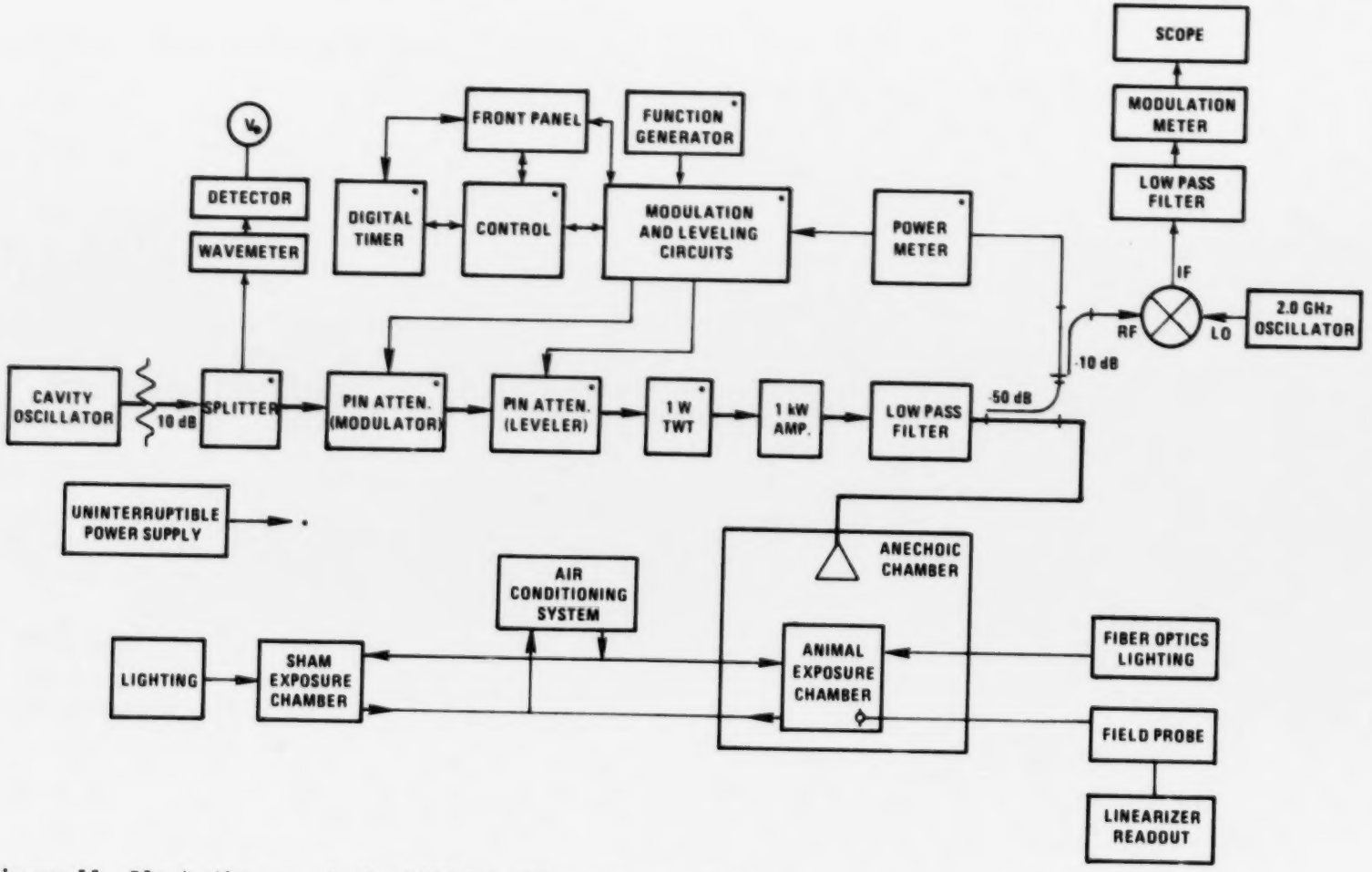


Figure 11. Block diagram of the 2450-MHz AM exposure facility.

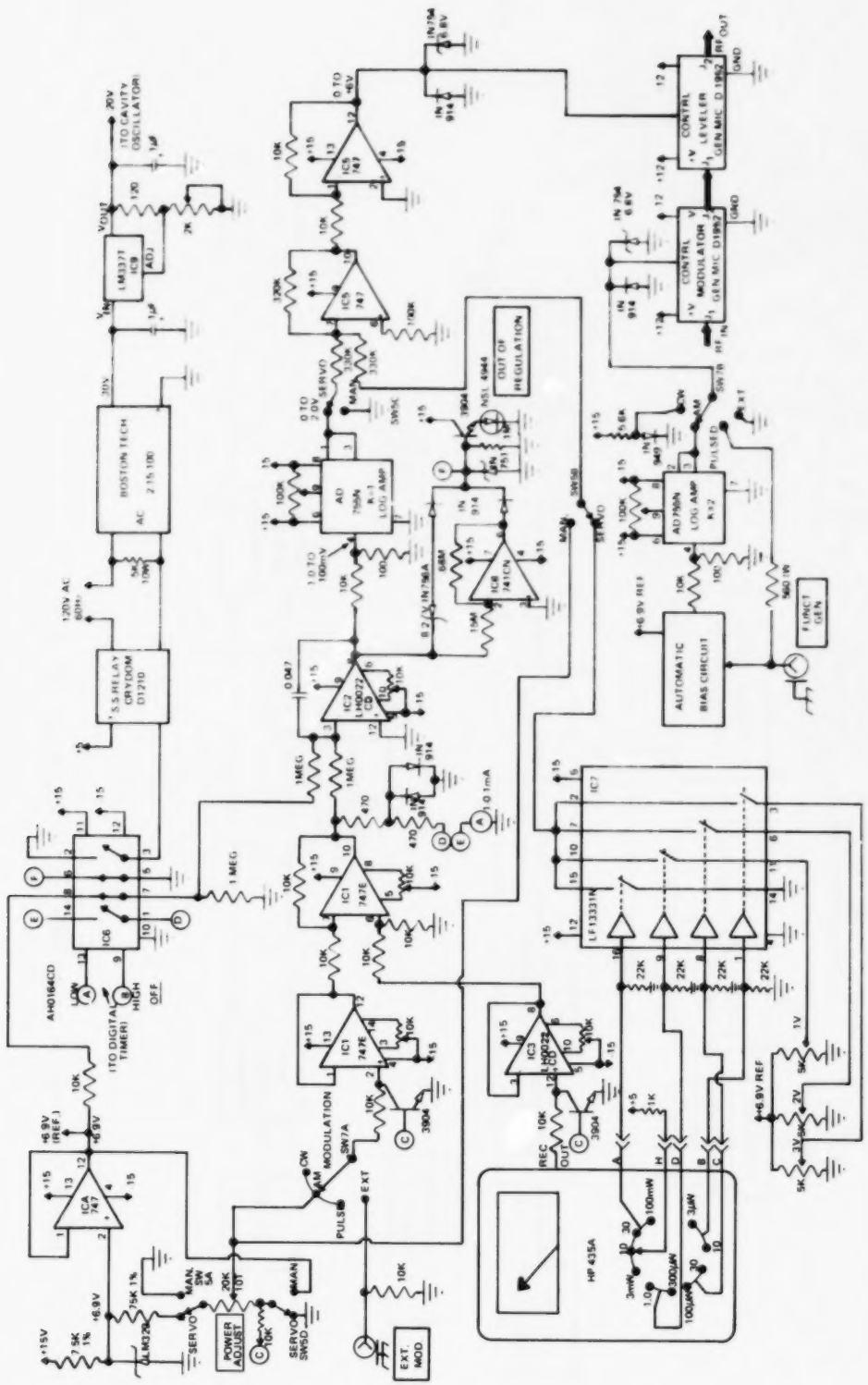


Figure 12. Modulation and leveling circuits.

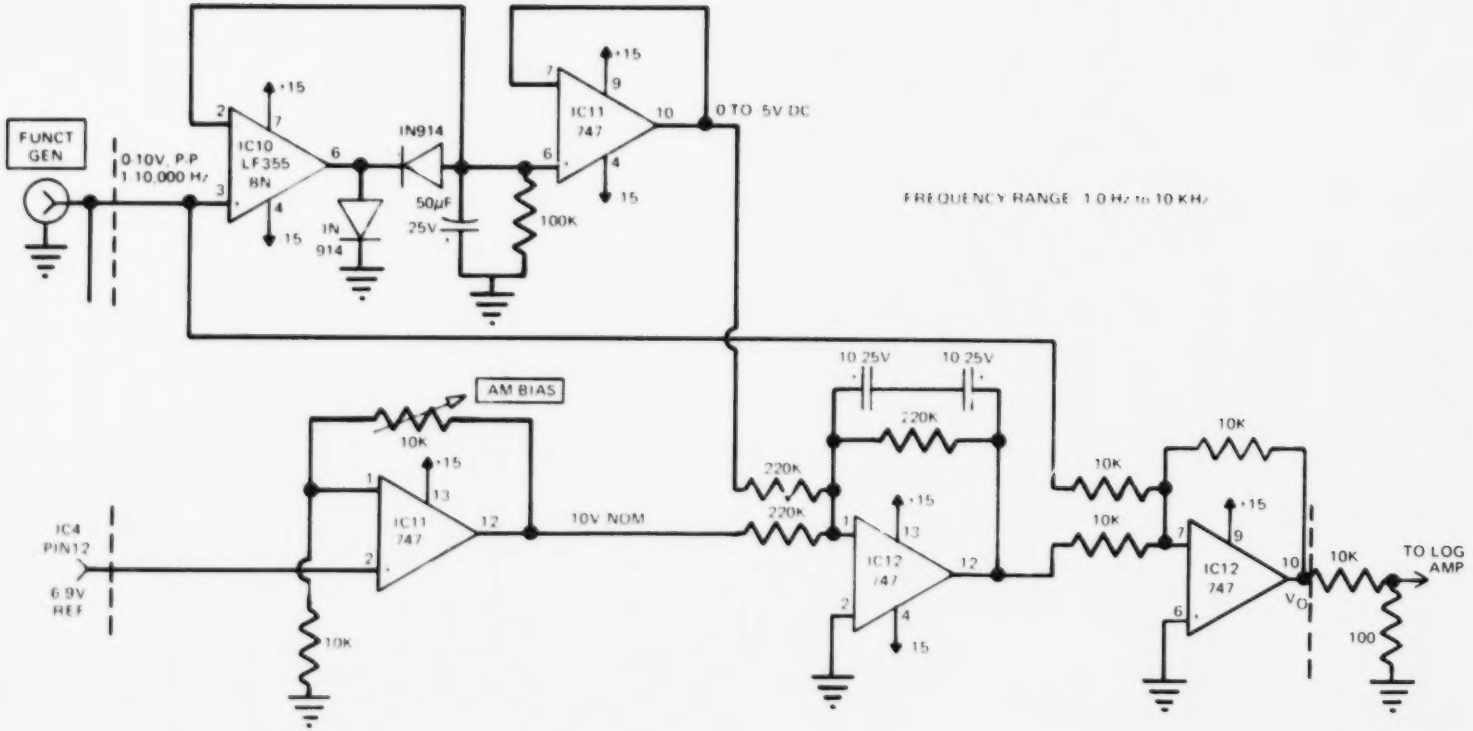


Figure 13. Auto-bias circuit.

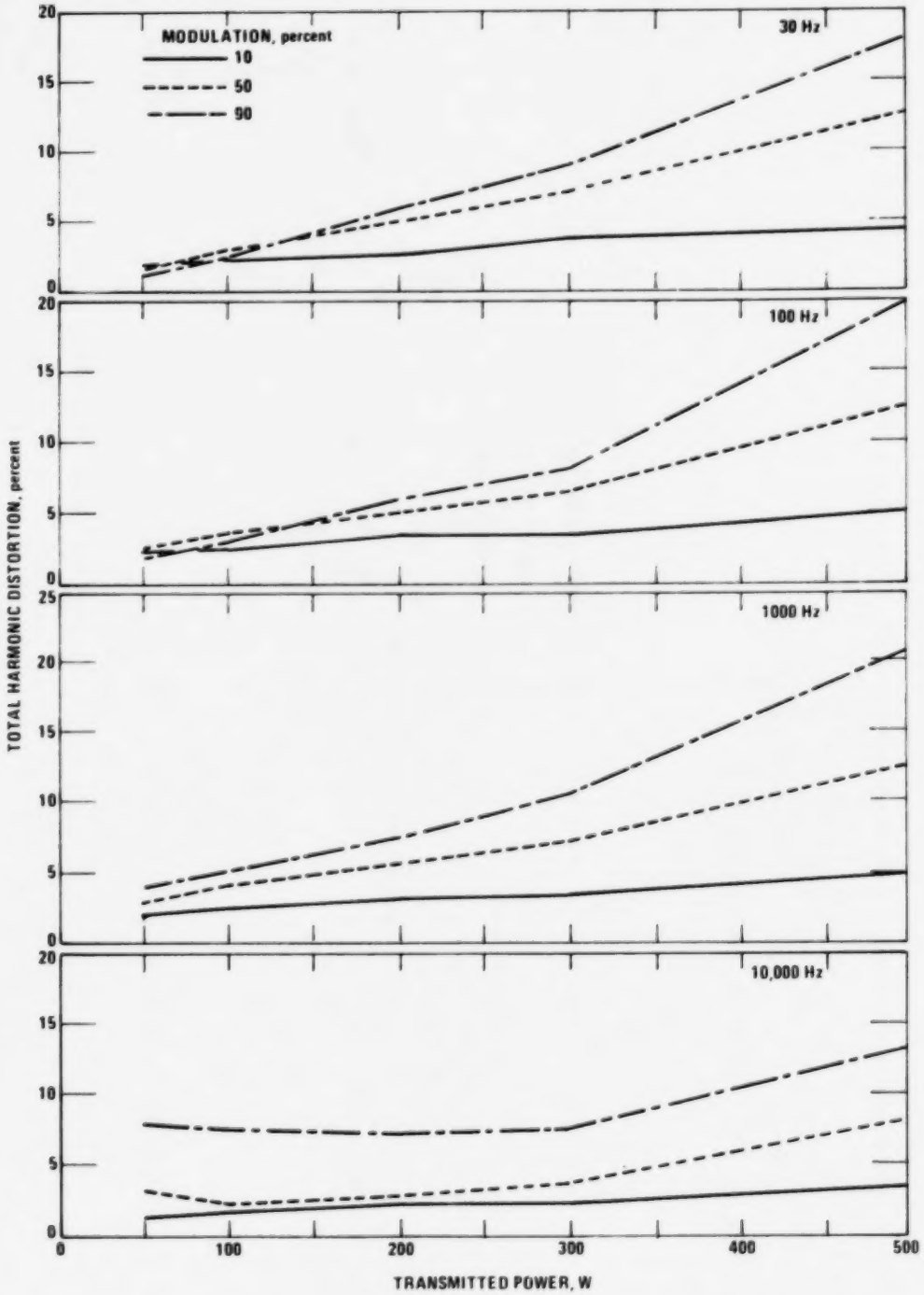


Figure 14. Plot of Total Harmonic Distortion versus transmitted RF power for various modulation frequencies with percent AM as a parameter.

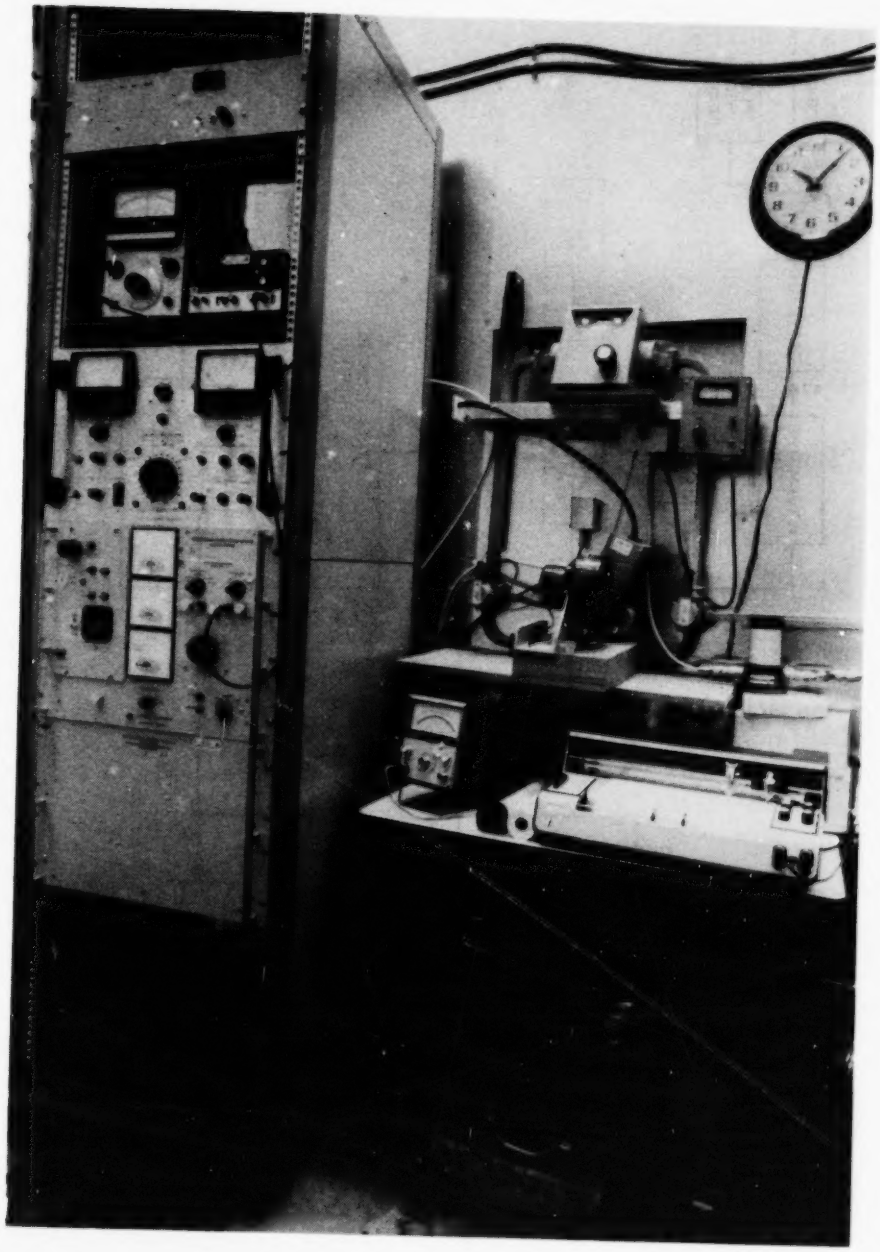
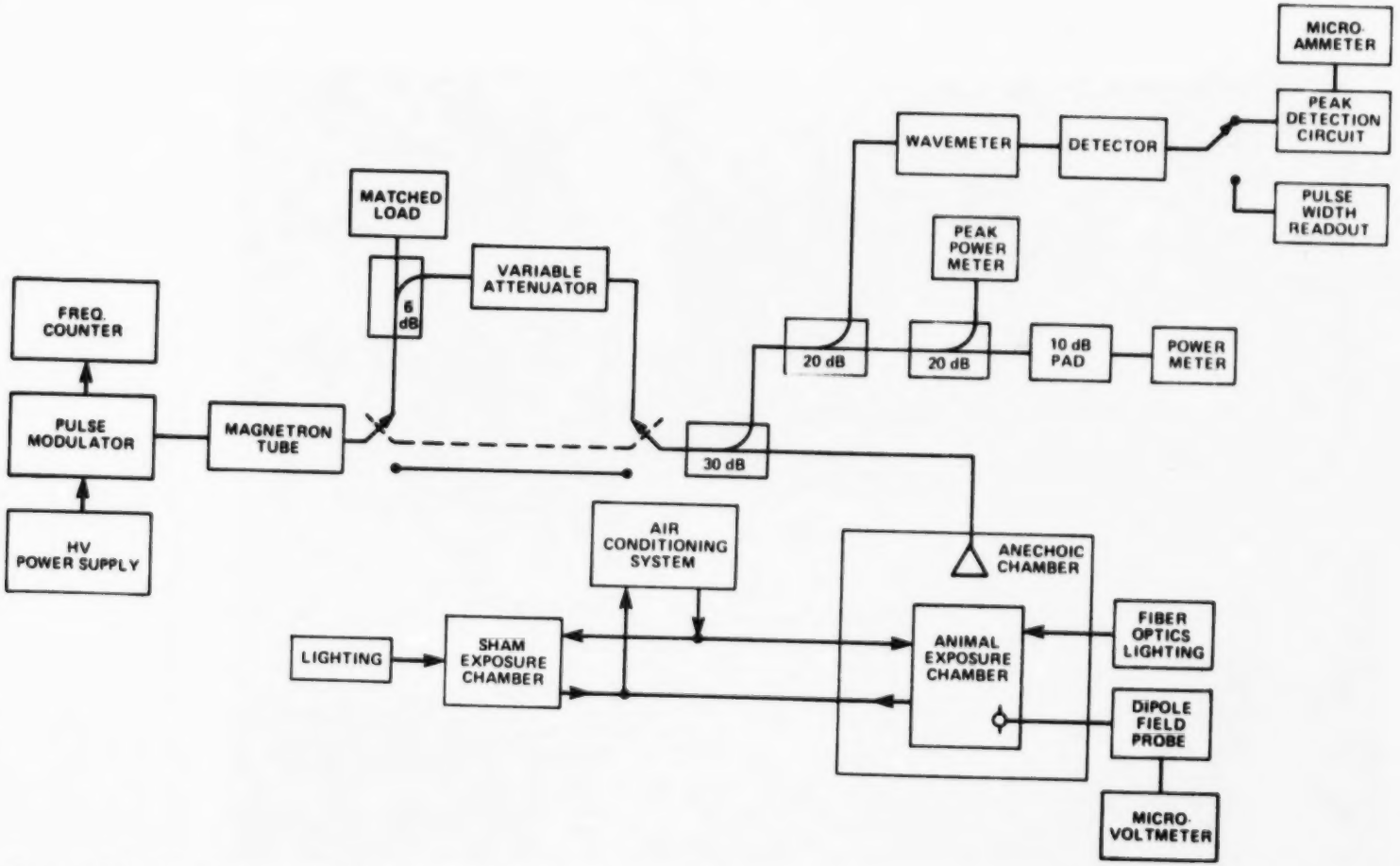


Figure 15. RF generation and control equipment.



Fugure 16. Block diagram of the X-Band exposure facility.

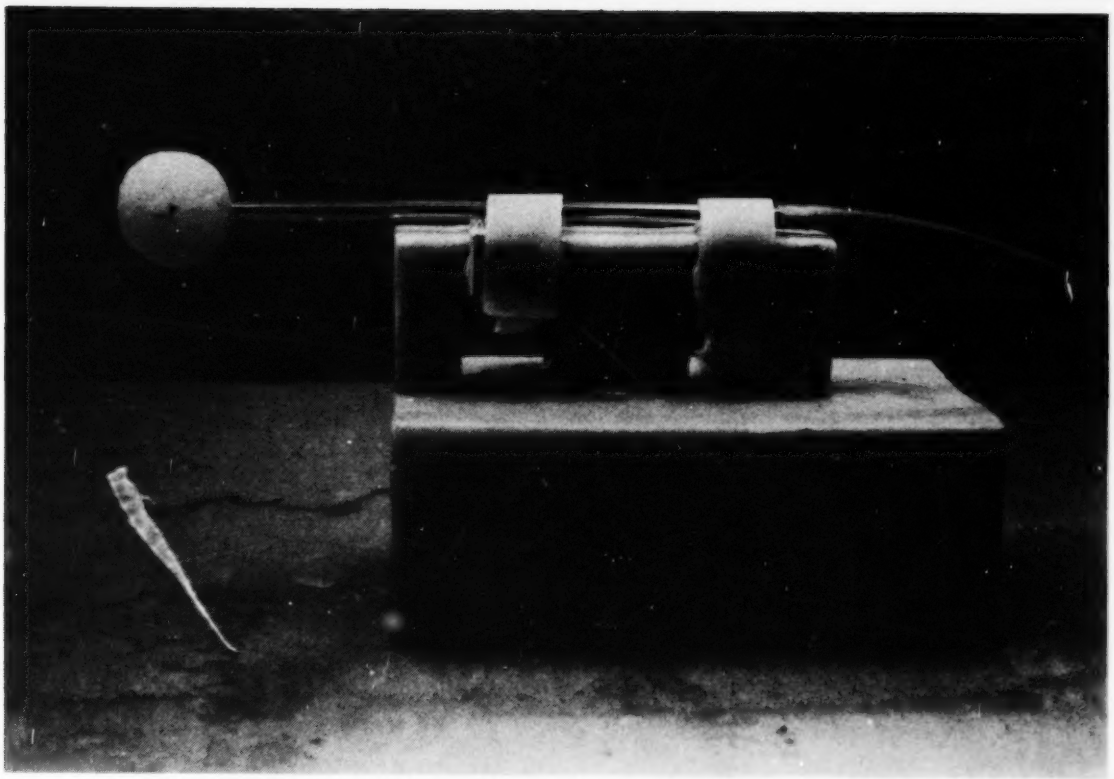


Figure 17. Single element dipole field probe.

*USGPO: 1983 — 659-095/0597